

# The Solar Wind and its Interaction with the Interstellar Medium

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## 1 Introduction and Basic Concepts

The solar wind is a stream of ions and electrons which flows outward from the Sun. This chapter discusses briefly the history of the solar wind, the source of the solar wind, the evolution of the solar wind with distance, solar cycle changes in the solar wind, and how the solar wind interacts with obstacles such as planets, comets, the interstellar medium, and other structures within the solar wind. The IGY in 1957 occurred at the dawn of the space age; fifty years of solar wind observations have provided a good understanding of many aspects of the solar wind. In the current IHY the solar wind interaction with the local interstellar medium (LISM) is being studied in situ for the first time and relatively soon we should have in situ measurements of the LISM.

Figure 1 shows a schematic diagram of the heliosphere. The top panel shows the plasma temperature and the bottom panel shows the H density. The arrows in the top panel show the flow of the solar wind and the interstellar plasma. The solar wind flows radially outward from the Sun until it reaches the termination shock, where it starts to turn and move down the heliotail in the direction of the LISM flow. The LISM is deflected at the bow shock and moves around the heliosphere. The heliopause is the boundary between the solar wind plasma in the heliosphere and the LISM plasma. This chapter discusses recent results on the interaction between the solar wind and the LISM.

A few basic physics principals are common themes of solar wind studies and are discussed here. The first is the concept of a frozen-in-magnetic field; simply, this means that the plasma and the magnetic field move together. If an ion or electron moves across a magnetic field line, it generates an electric field  $E = -V \times B$  which causes it to gyrate around the magnetic field line instead of moving past it. Since this electric field force is perpendicular to  $B$ , plasma is free to stream along the magnetic

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field lines, but to first order the plasma stays on the same magnetic field line. This constraint applies only to charged particles; neutral particles are not affected by the magnetic field and can flow across field lines.

The second concept is that of charge exchange and pickup ions. Charge exchange is a major mode of interaction between ions and neutrals. When these particles collide, the neutrals can lose an electron to the ion. The ion is now a neutral and continues moving in the same direction since it is not bound by the magnetic field. The new ion (the former neutral) is now bound by the magnetic field and is accelerated to the speed of the plasma. It has an initial thermal energy equal to that of the plasma flow energy. The energy for this heating and acceleration comes from the plasma flow energy, so the plasma slows down.

## 2 History

One of the first clues that the Sun had an outflowing wind came from observations of solar eclipses. When the solar surface was blocked by the moon, asymmetric streamers of material were observed. Changes in the Earth's magnetic field provided another piece of evidence; fluctuations were observed in compass needles which were called magnetic storms. These were linked to the Sun when it was noticed that the magnetic storm frequency was related to the sunspot number. In 1859, Carrington [1860] observed a large solar flare and realized it was related to a subsequent magnetic storm. With the invention of the spectroheliograph, many such correlations were observed. Chapman and Ferraro [1930] proposed that the Sun periodically ejected huge clouds of plasma which produced magnetic storms when they reached Earth.

Comets provided another clue about the nature of the solar wind. Dust and neutral gas surrounding the comet are pushed outward from the Sun by radiation pressure. A second tail is often observed at a small angle to the first. Hoffmeister [1943] in Germany, and later Biermann [1951], proposed that the Sun emitted a steady stream of particles, a "solar corpuscular radiation", which pushed the ions. This flow, now known as the solar wind, is a magnetized plasma; ions from comets are frozen onto this field and carried out with the solar wind. Since the solar wind flow is not always radial, a second tail is created.

The Sun's outer layer, or corona, is held down by the Sun's gravity. The corona is very hot, with a temperature of a million degrees, so the thermal particle motion is very fast. The fastest of these particles escape the Sun and form the solar wind. Parker [1958] developed an equation describing the solar wind escape and found that one viable solution was a plasma outflow which became supersonic and flowed continuously outward from the Sun and asymptotically approached a constant speed. Other solutions are also possible; one is a subsonic solar breeze which decreases in speed with distance. Mankind's entry into the space age resolved this question. The solar wind was supersonic, but highly variable [Gringauz, 1959; Neugebauer and Snyder, 1962].

### 3 Solar Wind Basics

The Sun has a magnetic field and rotates every 27 days; the field lines emanating from the Sun are connected to the solar surface and also rotate. The field is frozen-in to the outward flowing solar wind and thus carried outward with the plasma. The dipole field lines are stretched out by the outflow of the solar wind (Figure 2) so that the heliospheric current sheet (HCS) forms. The HCS separates field lines from north and south of the dipole equator; the field lines in these two (north and south) sectors are in opposite directions, outward in one hemisphere and inward in the other. Where the inward and outward field adjoin the change in field direction drives a current, thus the name current sheet. The feet of the field lines are anchored to the Sun and rotate with the Sun. Figure 2b shows how the this rotation results in the magnetic field lines moving out in a spiral pattern, called the Parker spiral. The tilt of the solar dipole causes the HCS to move up and down in heliolatitude, forming a wavy surface which has been compared to a ballerina skirt.

We have had solar wind observations for almost 50 years, with fairly continuous solar wind monitoring since the early 1970s. Table 1 shows average, median, maximum and minimum values measured by the Wind spacecraft near Earth from 1994-2007. The extreme variation of the solar wind is demonstrated by the table, with changes of almost a factor of ten in speed, a factor of 1000 in density, 25 in thermal speed (625 in temperature), and 300 in magnetic field strength. Most solar wind ions are protons, but  $\text{He}^{++}$  is also observed with density ratios which range from near 0 to 30%. For a solar wind speed of 440 km/s, the average Parker (magnetic field) spiral angle at Earth would be about  $45^\circ$ ; peaks in the distribution of East/West magnetic field angles are observed at this angle as predicted.

This already fairly complex picture is further complicated both by long-term changes which occur over a solar cycle and short-term transients such as those which drive magnetic storms. The 11-year solar cycle has been observed in sunspot numbers for centuries. By definition sunspot numbers peak at solar maximum and are a minimum at solar minimum. The magnetic field strength varies by about a factor of 2 over the solar cycle, peaking at solar maximum. The direction of the Sun's dipole changes every solar cycle. At solar minimum, solar magnetic field is roughly dipolar and the current sheet is most closely aligned with the solar equator, whereas at solar maximum the field is highly tilted and has strong non-dipolar components. The configuration of the solar wind also changes dramatically. At solar maximum, the solar wind speed is slow (400 km/s) with average densities of  $7 \text{ cm}^{-3}$  at all heliolatitudes. At solar minimum, coronal holes, regions of open magnetic field lines, cover the solar poles and extend to low heliolatitudes. Solar plasma can flow out along these open field lines at high speeds, 700 - 800 km/s with densities of  $3\text{-}4 \text{ cm}^{-3}$ . At solar minimum the heliolatitudinal gradient in solar wind speed and density is large. Between solar maximum and minimum the solar wind evolves between these two states. Figure 3 from Ulysses illustrates these differences; the data from the first orbit at solar minimum showed high solar wind speeds above  $30^\circ$  heliolatitude and low speeds nearer the equator. The right panel shows that near solar

maximum speeds are much more variable with only small regions of high-speed flow.

The amount of  $\text{He}^{++}$  also varies over a solar cycle, with more He at solar maximum than at solar minimum [Ogilvie and Hirshberg, 1974; Feldman et al., 1978; Aellig et al., 2001]. Wind observations show that the He/H ratio varies linearly with speed during solar minimum but is not a function of speed during solar maximum. Figure 4 shows histograms of the He/H abundance at solar minimum, solar maximum, and in between for only the slow solar wind. At solar minimum most solar wind has low He/H abundances. Between solar maximum and minimum a bi-modal distribution with both low and high He/H values is observed. At solar maximum, most of the solar wind has high He/H ratios but there is still a small peak at very small ratios. These data suggest that a constant low-speed, low He/H solar wind source is always present near the HCS which dominates observations near solar minimum when the HCS tilt is small but makes up a small part of observations when the tilt is large (and Wind sees less flow from near the HCS). These two peaks in the He/H ratio suggest that the slow solar wind has two separate sources.

## 4 Radial Evolution of the Solar Wind

The solar wind evolves with distance. Figure 5 shows the solar wind speed, density, and thermal proton temperature variation with distance observed by Voyager 2. Superposed on the V2 speed profile are the speeds observed at 1 AU. Inside 30 AU the speeds at Earth and those at V2 are very similar. The solar wind parameters have a lot of variation, but to first order the speed is constant, the density decreases as  $R^2$ , and the temperature decreases out to 20-25 AU and then increases. The gradient in speed with heliolatitude at solar minimum causes the deviation of solar wind speeds at Earth and V2 in 1986-87 and 1995-98. In 1986-87, V2 is at a lower average heliolatitude than Earth and observes lower speeds while in 1995-98 V2 is at higher heliolatitude than Earth and observes much higher speeds. In addition to the solar cycle changes, speed variations with a 1.3-year period were observed from 1987-1998 [Richardson et al., 1995]. This variation in speed was observed throughout the heliosphere [Gazis et al., 1995] and has been an occasional feature observed in historic solar wind data [Silverman, 1992]. A similar period has been observed in convection patterns in the Sun and may be related [Howe et al., 2000].

The interplanetary coronal mass ejections (ICMEs, see chapter by Gopalswamy) prevalent near and after solar maximum have strong effects on the solar wind evolution. When a series of ICMEs occurs, the first one runs into the ambient solar wind and is slowed. Subsequent ICMEs catch up and merge with the first ICME. By the time these ICMEs reach the outer heliosphere many have combined forming merged interaction regions (MIRs), regions of increased speed, density, dynamic pressure, and magnetic field [Burlaga, 1995]. In 2002-2005, V2 observed a series of these structures, roughly 2 per year lasting 30-60 days, with factor of 10 increases

in the dynamic pressure. These large increases in dynamic pressure can drive the termination shock (TS) outward by 3-4 AU [Zank and Mueller, 2003].

## 5 Obstacles in the Solar Wind

The solar wind does not move outward unimpeded. In the heliosphere many small obstacles such as the planets, moons, comets, dust, and neutral atoms affect the local solar wind. But most of the solar wind is eventually deflected down the heliotail and eventually merges with the flow of the interstellar medium. We describe these different interactions.

The simplest interaction is with non-conducting obstacles with no atmospheres like the moon and most asteroids. The magnetic field lines move right through these bodies but the plasma cannot; it runs into the surface and is absorbed. A plasma void is formed behind the moon, which results in a pressure gradient force in the solar wind towards the depleted region. But the plasma can only move along magnetic field lines so, as shown in Figure 6, the plasma streams into the depletion region from two directions. On one side the pressure force results in an increase in the ambient speed and in the other it results in a decrease.

Conducting obstacles have a more complex interaction since the magnetic field cannot pass through them but must move around them. Planets with magnetic fields have magnetospheres, regions dominated by the planet's magnetic field, which are 1 to 100 times the size of the planet. The size of the magnetosphere is determined by pressure balance between the solar wind dynamic pressure and the combined pressure of the planet's magnetic field and plasma. Since the solar wind pressure varies with time, so do the magnetosphere sizes. The solar wind must flow around these magnetospheres.

Planets and comets which do not have magnetic fields but which have atmospheres (Venus, Mars, Titan) also form conducting obstacles. The upper layers of the atmosphere are ionized by solar photons and by charge exchange with the solar wind and form an ionized layer called the ionosphere. The solar wind magnetic field compresses this plasma (since the field can't move through a plasma) until ion pressure equals solar wind pressure, a boundary called the ionopause at planets and the cometopause at comets. The solar wind must flow around these boundaries of the conducting plasma.

The solar wind is supersonic, thus it must go through a shock before it can divert around an obstacle. The fastest wave speed in the solar wind is the fast mode speed, which is the square root of the sum of the squares of the sound speed and the Alfvén speed. At a fast mode shock, the density, temperature, and magnetic field increase. Two types of fast mode shocks are present in the solar wind; those in front of planets and comets are called reverse shocks since these shocks are essentially standing waves which move in the reverse direction to the solar wind flow. At a reverse shock, the speed decreases and the flow direction changes downstream as the solar wind starts to flow around the magnetosphere. The shock upstream of the

obstacle is called a bow shock and the region of solar wind downstream of the shock is called the magnetosheath. Sheath regions have highly variable plasma and field parameters.

The interstellar medium is a very large conducting obstacle, a magnetized plasma in which roughly 1/3 the gas is ionized. Figure 1 shows that the solar wind makes a large bubble of solar material in the LISM. The boundary of the solar wind is determined by where the solar wind dynamic pressure balances the dynamic, thermal, and magnetic pressure of the LISM. This boundary is called the heliopause. Analogous to a magnetopause, inside the heliopause all the plasma is solar and outside all is from the LISM. The solar wind must turn and flow in the LISM direction, so a reverse shock, called the termination shock, forms at which the density, temperature and magnetic field increase and the speed decreases. At the TS the flow starts to turn so as to eventually flow down the heliotail.

We mentioned above that the Sun is much more active at solar maximum; much of this activity is in the form of coronal mass ejections (CMEs) which are huge eruptions of material outward from the Sun. These large plasma structures propagate outward through the solar wind where they are called interplanetary CMEs, or ICMEs. ICMEs are ejected with a wide distribution of speeds; fast ICMEs have speeds of several thousand km/s near the Sun. The fast ICMEs run into the solar wind ahead; again, since the flow is supersonic, a shock forms so that the leading solar wind can flow around the faster ICME plasma. In this case the shock moves ahead of the ICME plasma and is a fast forward shock; the density, temperature, field, and speed all increase at the shock. The ambient solar wind turns at the shock so that it can flow around the ICME (in the ICME frame).

A similar situation to the ICME interaction develops between solar minimum and solar maximum when coronal holes and their fast solar wind extend to low latitudes. As the Sun rotates, fast and slow streams are alternately emitted from the Sun. The fast wind catches up to the slow wind and again a shock must form, but in this case two form. A fast shock propagates upstream into the slow wind and a reverse shock propagates into the fast wind. These features are called forward-reverse shock pairs.

The interstellar medium starts to affect the solar wind well before the TS. Although the ions cannot pass through the heliopause, the neutrals in the LISM are not bound by the magnetic forces and move into the heliosphere. The helium reaches Earth essentially unchanged from the LISM except for the acceleration of the Sun's gravity. The LISM H is coupled to the protons in the heliosheath via charge exchange and thus is slowed, heated, and diverted in flow direction compared to the He.

These neutrals are ionized, the He inside 1 AU and the H throughout the heliosphere until they are mainly gone inside 5 AU. The pickup ions formed from these neutrals are accelerated up to the solar wind speed and have an initial temperature equal to the solar wind energy, about 1 keV. Figure 7 shows the density of the various species near and in the heliosphere. The LISM ions increase in density at the bow shock and do not cross the heliopause (HP). The solar wind ions decrease in density as  $R^2$ , increase at the TS, and do not cross the HP. The LISM neutrals enter the heliosphere and are slowly lost via charge exchange. The neutral LISM is the

densest component in the heliosphere outside about 10 AU. The pickup ions are the ionized LISM neutrals. Their density decreases with distance, then jumps at the TS. By the TS, almost 20% of the ions are pickup ions. Since the pickup ions are hot, they dominate the solar wind thermal pressure outside about 30 AU. Thus even before the TS the LISM has significant impact on the inner heliosphere through the neutral component.

Figure 5 compares the solar wind speeds observed at 1 AU with those observed by V2. Outside 30-40 AU the V2 speeds are systematically lower than those at 1 AU. The speed decrease at V2 is a result of the ionization of the LISM neutrals and their subsequent acceleration to the solar wind speed at the expense of the energy in the thermal solar wind. The ratio between the solar wind slowdown and the pickup ion density is  $NP/NT = 7/6 DV/V$  [Richardson et al., 1995; Lee, 1995], where  $DV$  is the solar wind slowdown,  $V$  is the speed of the solar wind,  $NP$  is the pickup ion density, and  $NT$  is the total ion density. Observations show that the slowdown is about 17% near the TS, so roughly 30% of the solar wind flow energy has been converted to particle energy before effects of the TS are observed.

The increase in temperature outside 20-30 AU in Figure 5 is also caused by the pickup ions. They are formed with a ring distribution (all their energy is perpendicular to the magnetic field) which is unstable. This instability generates magnetic fluctuations which heat the thermal ions; only about 5% of the energy generated by relaxing the ring distribution is needed to provide the observed solar wind heating [Smith et al., 2006; Isenberg et al., 2005].

We mentioned above that the TS location results from a balance between the solar wind and LISM pressures. But until 2004, we did not know the LISM pressure and so we did not know the TS location. The first sign that Voyager was approaching the TS was the observation of particles streaming along magnetic field lines from the TS to V1 starting at 85 AU. Since the TS is not circular, some parts of a field line may cross the TS while others are in the solar wind. The particles heated at the shock can stream along the magnetic field lines into the heliosphere; this region of streaming particles is called the termination foreshock and is analogous to foreshock regions observed upstream of planetary bow shocks. The particle intensities vary as the connection of the field lines to the TS changes. These particles were observed at V1 roughly 2 1/2 years before the TS crossing.

In December 2004, V1 crossed the TS at 94 AU [Decker et al., 2005; Burlaga et al., 2005; Stone et al., 2005]; this event revealed the scale size of the heliosphere. Unfortunately the plasma instrument on V1 is not working so the solar wind ions were not observed and the TS crossing occurred in a data gap. V2 started observing the foreshock particles about the same time V1 crossed the TS at 75 AU, 10 AU closer than V1 and these particles were streaming in the opposite direction [Decker et al., 2006]. These observations support the hypothesis that the TS is blunt or flattened at the nose. V1 and V2 are on opposite sides of the nose, so particles coming to V1 and V2 from the nose are from opposite directions [Jokipii et al., 2004]. Thus the foreshock particles told us about the shape of the heliosphere.

The difference of the foreshock boundary in the V1 and V2 directions suggested that the heliosphere might be asymmetric, with the TS and HP closer in the south

(where V2 is) than the North (where V1 is). When V2 crossed the TS in August 2007 it was at 84 AU, 10 AU closer than at V1 [Decker et al., 2008; Burlaga et al., 2008; Stone et al., 2008; Richardson et al., 2008]. The location of the TS depends on the solar wind dynamic pressure which varies with time. Over a solar cycle average solar wind dynamic pressure varies by a factor of 2 [Lazarus and McNutt, 1990], causing the TS to move in and out over a range of 10-14 AU [Karmesin et al., 1995; Wang and Belcher, 1998]. If we account for the pressure change in the solar wind from 2004 to 2007, the TS asymmetry is 7-8 AU with the TS closer in the V2 than the V1 direction. One possible explanation for this asymmetry is shown in figure 8; if the solar wind magnetic field is tilted from the direction of the LISM flow then the field is more compressed (and thus stronger) on one side of the heliosphere, leading to an asymmetry [Linde et al., 1998; Ratkiewicz et al. 1998; Opher et al., 2006; 2007; Pogorelov et al., 2006; 2007].

The V2 TS crossing provided the first plasma data near the TS and the first time we had data at the TS itself. The TS differed from other shocks in the solar system in a few significant ways. The decrease in speed began 0.7 AU upstream of the TS; the solar wind speed dropped from 400 km/s to 300 km/s at the TS in 3 steps. At other shocks the speed decrease has all occurred at the shock. The shock was relatively weak; the density and field jumps were a factor of 2 compared to a factor of 4 at planetary bow shocks. The thermal plasma was heated relatively little, to 100,000 K compared to 2,000,000 K in planetary magnetosheaths. We think all the flow energy goes into the pickup ions instead of the thermal ions [Zank et al., 1996; Gloeckler et al., 2006].

Thus in the past few years we have revolutionised our understanding of the heliosphere's interaction with our interstellar environment. We know the size of the heliosphere is about 90 AU, that the TS is not round but blunt, and that the heliosphere is asymmetric. As the Voyagers continue moving outward they will eventually enter the LISM and measure it directly. The location of the HP will not be known until we cross it, but models suggest the width of the heliosheath is 30-40 AU so that the Voyager could cross it in 2014-2018. One indication the HP is approaching is that the heliosheath flow will rotate parallel to this HP boundary. Another indication may be an increase in the magnetic field as it piles up against this boundary [Cranfill, 1971]. These spacecraft have sufficient power to continue several years past 2020, so there is a good chance they will make mankind's first measurements of the plasma outside our solar system.

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**Fig. 1** A model showing the plasma temperature and flow lines (top) and the neutral H density (bottom). The heliospheric boundaries are labeled. Figure courtesy of H. Muller

**Fig. 2** As the solar wind moves outward the magnetic field is stretched so that a current sheet forms between the inward and outward field lines (left panel). The rotation of the Sun causes the field lines to spiral outward and the tilt of the solar wind field causes the current sheet to move up and down (right panel)

**Fig. 3** The solar wind as a function of latitude at solar minimum (left) and solar maximum (right) observed by Ulysses. Figure from McComas et al., 2001.

**Fig. 4** Ratio of He/H in the slow ( $\sim 400$  km/s) solar wind for three phases of the solar cycle. Figure courtesy of J. Kasper.

**Fig. 5** Speed, density, and temperature versus radial distance observed by Voyager 2. The speeds observed at 1 AU are superposed.

**Fig. 6** The solar wind is absorbed by the moon, leaving a vacuum in the moon's wake which is filled by plasma streaming along the field lines. From Steinberg et al., 1997.

**Fig. 7** The density of the plasma and neutral components of the solar wind and LISM. Figure Courtesy of R. Mewalt.

**Fig. 8** One model showing the formation of an asymmetric heliosphere caused by field lines draping around the south. Figure courtesy of M. Opher.